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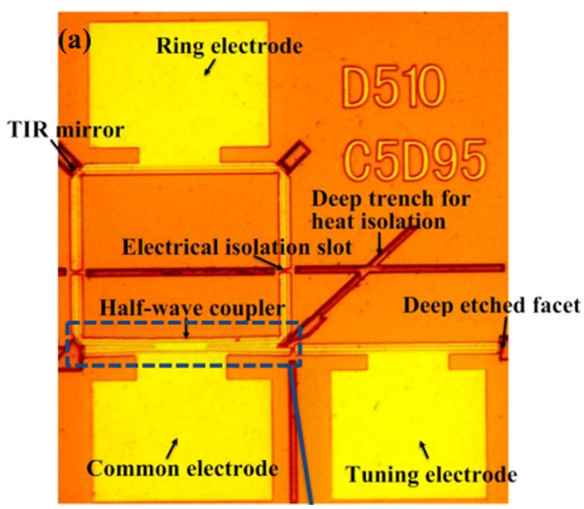

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Half-Wave-Coupled Ring-FP Laser With 50-Channel 100-GHz-Spaced Wavelength Tuning

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Abstract: We report our latest experimental results of the half-wave-coupled rectangular ring-FP laser. All the waveguides of the device are active, and the thermooptic effect is employed to extend the tuning range beyond the free-spectral-range limit. Single-electrode tuning of 20 channels with 100-GHz spacing is obtained. By combining five single-electrode-controlled tuning curves with different bias currents on fixed electrodes and with the thermoelectric cooler fixed at 20 °C, wavelength tuning of 50 channels with 100-GHz spacing covering the L-band is achieved with a side-mode suppression ratio up to 41 dB. Direct modulation at 2.5 Gb/s is also demonstrated. The simple and compact ring-FP laser has great potential as a low-cost tunable laser for many applications.

Index Terms: Tunable semiconductor laser, half-wave coupler, rectangular ring.

1. Introduction

Low-cost widely wavelength tunable semiconductor lasers are key components for applications in optical communications and data center interconnects. Many different types of tunable lasers based on gratings have been investigated and developed [1], [2], such as sampled grating (SG) distributed Bragg reflector (DBR) laser [3], superstructure grating (SSG) DBR laser [4], digital super mode (DS) DBR laser [5], modulated grating Y-branch (MG-Y) laser [6] and DFB arrays [7]. They all require sophisticated fabrication process of gratings and epitaxial regrowth, and at least three electrodes for wavelength control, which makes these lasers very expensive, and has limited their wide deployment. Tunable lasers based on ring resonators have also been developed [8]–[12]. While the requirement for the complex grating fabrication is eliminated, they still require at least three electrodes for controlling the wavelength, including a phase control electrode. The etch-and-regrowth process for active-passive integration is still needed, and the chip sizes are also very large.

Simpler design such as the cleaved-coupled-cavity (C^3) structure have been developed in the 1980's [13], but due to the poor side mode suppression ratio (SMSR), they have not been widely used in practice. Similar designs known as slotted Fabry-Perot (SFP) laser [14], [15] with several slots etched in an FP cavity were reported with large SMSR. However, the size and position of the etched slots needs to be controlled precisely, which is difficult especially when the laser

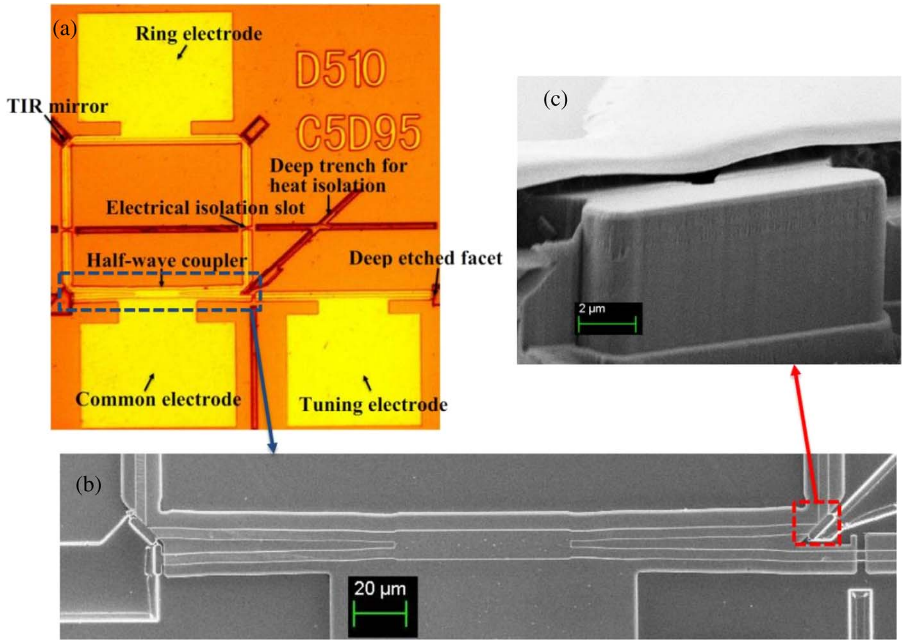


Fig. 1. (a) Optical microscope image of the half-wave coupled rectangular ring-FP laser; (b) SEM picture of the half-wave coupler; and (c) SEM picture of the etched mirror.

is designed to be tunable employing the Vernier effect [16], because the precise phase relationships need to be maintained across the whole tuning range. This would increase the fabrication difficulty, and the scattering loss brought by the slots will also degrade the laser performance. Moreover, the length of the SFP is still very long.

In order to achieve simple and compact tunable lasers, we recently proposed and demonstrated a half-wave coupled V-cavity laser [17]–[19] and a half-wave coupled rectangular ring-FP laser [20]. They involves only two resonators, either FP or ring type, without any grating or epitaxial regrowth. They also have smaller chip size and fewer electrodes compared to those based on complex gratings and cascaded ring filters. The tuning algorithm is therefore much simpler because they do not require synchronized multi-electrode tuning. These advantages make them promising for cost-sensitive applications such as data center and optical access networks.

The V-cavity laser, which has two FP cavities, used three etched facets. Without high reflectivity coating, the threshold current would be high. The ring-FP laser is an alternative that can lower the total threshold current and improve the SMSR compared to the V-cavity laser without using reflective coatings, because the rectangular ring with total internal reflection (TIR) mirrors brings less loss than the etched mirror of the FP cavities.

We previously reported a rectangular ring-FP laser with 8-channel 200 GHz spaced wavelength tuning [20]. In this paper, we report our latest experimental results on the half-wave coupled rectangular ring-FP laser with 50-channel 100 GHz spaced wavelength tuning. With improved design, the maximum SMSR of single mode emission reached 45.6 dB. Single-electrode-tuning of 20 channels with 100 GHz spacing is obtained. By combining five tuning curves of single-electrode-tuning with different bias currents on fixed electrodes, wavelength tuning of 50 channels covering L band is achieved with SMSR up to 41 dB, with the thermo-electric cooler fixed at 20 °C. Direct modulation at 2.5 Gbps is also demonstrated.

2. Device Principle and Fabrication

Fig. 1(a) shows the optical microscope image of the half-wave coupled rectangular ring-FP laser. The rectangular ring resonator couples to the FP cavity from one side of the rectangle by a half-wave coupler [20]. The half-wave coupler has been described in [17], [21]. For a half-wave coupler, the phase difference between the bar coupling coefficient and the cross coupling coefficient is π, in contrast to conventional directional couplers or multimode interference (MMI) couplers which have a phase difference of $\pi/2$ (quarter-wave coupler). Three electrodes are used. The tuning electrode is used for wavelength tuning. The common electrode is used for providing gain and modulation signal. The ring electrode is used for gain and fine tuning. The rectangular ring resonator combined with the half-wave coupler generates comb-like transmission spectrum for mode selection and the gain within the ring can make the transmission peak sharper which improves the SMSR. In order to achieve single mode operation and wide tuning range, the Vernier effect between the rectangular ring resonator and the FP cavity is used to obtain a large enough free spectral range (FSR) so that only one longitudinal mode can reach its threshold within the active material gain window. Moreover, all the waveguides of the device are active and the thermo-optic effect is employed to extend the tuning range beyond the FSR limit.

The perimeter of the ring resonator is designed to be 932 μm so that the channel spacing matches the 100 GHz ITU-T grid, and the FP cavity is 510 μm long in order to employ the Vernier effect. Consequently, the FSR of the rectangular ring-FP laser is about 8 nm. The half-wave coupler is optimized using the method introduced in [20] so that the rectangular ring-FP laser can obtain its maximum threshold gain difference between the lasing mode and the adjacent longitudinal modes. Fig. 1(b) is the SEM picture of the half-wave coupler. The bar coupling coefficient C_b and cross coupling coefficient C_x of the designed couplers are 0.82 and -0.18, respectively. The corresponding calculated threshold gain difference between the main mode and the adjacent side mode is 6.4 cm^{-1}. Fig. 1(c) shows the SEM picture of the turning mirror with vertical and smooth sidewall. The total device size is only 0.5×0.5 mm^2.

A standard ridge waveguide laser structure with InGaAsP/InP multiple quantum wells (MQW) was used to fabricate the laser. The layer structure of the laser consists of 0.2 μm heavily Zn-doped $In_{0.53}Ga_{0.47}As$ cap, 1.65 μm Zn-doped InP upper cladding, 0.05 μm InGaAsP step-graded index separate confinement layers with the bandgap wavelength λ_g varying from 1.05 μm to 1.25 μm, five 5.5 nm undoped 1% compressively strained InGaAsP quantum wells and six 10 nm 0.3% tensile-strained InGaAsP barriers, 0.05 μm InGaAsP step-graded index separate confinement layers, and 1.5 μm Si-doped InP buffer on n-doped substrate. A total of two etching depths are used in the device: a shallow etch for the waveguides, and a deep etch for the reflecting mirrors. All the waveguides are 3 μm wide and 1.7 μm high. The TIR mirrors are fabricated in a deep ($\sim$4 μm) etching step with a self-aligned process, together with the deeply etched facets for the FP cavity. To verify the quality of the deep etched facets, FP lasers with 500 μm long and 3 μm wide waveguide are fabricated with both etched facets and cleaved facets. The measured threshold current is around 25 mA for both lasers, with negligible difference.

3. Experimental Results and Discussions

The laser is tested after being mounted on an aluminum nitride chip carrier with a thermo-electric cooler (TEC) controlled at 20 °C. The injection currents on the ring electrode, the common electrode and the tuning electrode are denoted as I_r, I_c, and I_t, respectively. The rectangular ring-FP laser reaches its threshold when $I_r = 28$ mA, $I_c = 32$ mA, and $I_t = 21$ mA, for a total threshold current of about 81 mA. The maximum SMSR of the single mode emission reaches 45.6 dB as shown in Fig. 2(a). When $I_r = 65$ mA, $I_c = 146$ mA, and $I_t = 80$ mA, 14 mW output power is measured by a broad area photodetector. We can estimate from Fig. 2 that the FSR of the rectangular ring-FP laser is about 8 nm as designed.

The LIV curve is measured when $I_r = 61.9$ mA, $I_t = 79$ mA as shown in Fig. 2(b). The slope efficiency ranges from 0.171 W/A at low current to about 0.085 W/A at high current. The series resistance of the common electrode is about 6.5 Ohm. No mode hop is observed when the current on the common electrode is varied.

Single-electrode-tuning of 20 consecutive channels with 100 GHz spacing is obtained as shown in Fig. 3(a), when increasing the injection current on the tuning electrode from 40 mA to

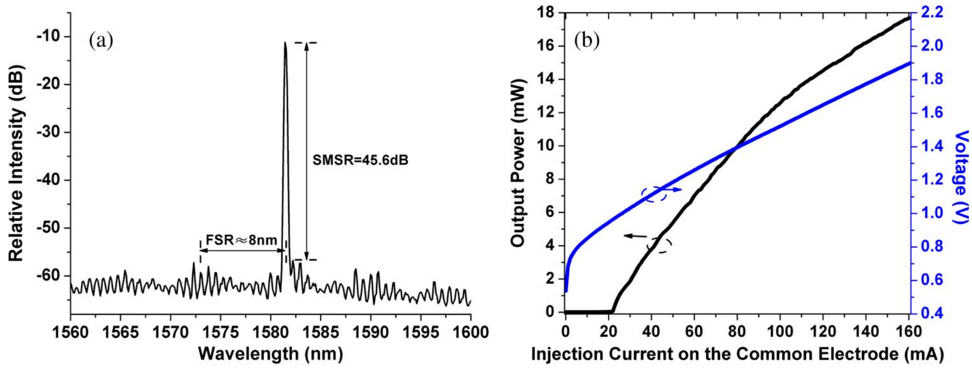


Fig. 2. (a) Single mode emission spectrum of a rectangular ring-FP laser with 45.6 dB SMSR. (b) LIV curve when $I_r = 61.9$ mA, $I_t = 79$ mA.

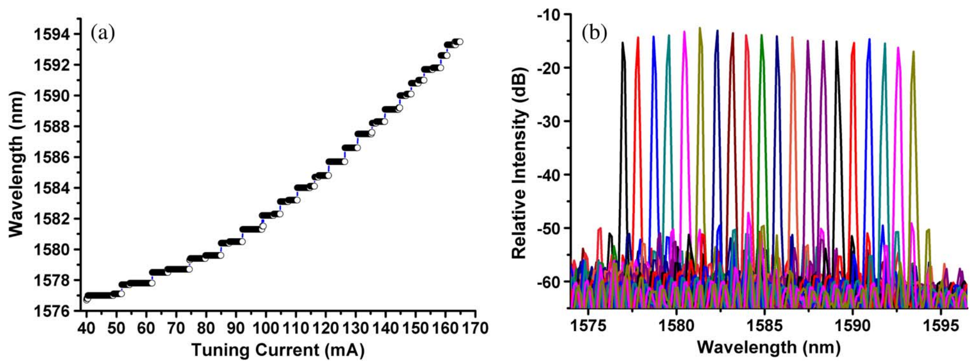


Fig. 3. (a) Measured single-electrode-controlled tuning curve and (b) corresponded superimposed spectra of the 20-channel switching.

164 mA, and keeping the injection currents on the common electrode and the ring electrode fixed at 137.9 mA and 72.8 mA, respectively. Fig. 3(b) shows the corresponding superimposed spectra of the 20-channel switching. The SMSR varies from 33 dB to 41 dB. The total tuning range is about 16.5 nm, before the wavelength jumps by one FSR (about 8 nm). The large tuning range beyond the FSR limit is mainly caused by the red shift of the material gain spectrum with increasing temperature due to the increased tuning current. It can be deduced from the tuning curve of Fig. 3(a) that the gain spectrum shift is about 8.5 nm when the tuning current increases from 40 mA to 164 mA. It should be noted that the ring electrode can also be used to tune the wavelength. However, unlike tuning using the tuning electrode, when increasing the injection current on the ring electrode, the lasing wavelength of the rectangular ring-FP laser would shift to shorter wavelength, which is on the opposite direction as compared with the gain spectrum shifts when increasing injection current. This results in a smaller tuning range than the FSR. Therefore, the co-directional tuning on the tuning electrode is preferred for extending the tuning range. The channel spacing is about 108 GHz in Fig. 3(a) which is a little larger than the design value of 100 GHz, because of the deviation of the waveguide dimensions and the effective group index. This can be easily corrected in the future design by increasing the perimeter of the rectangular ring.

Note that unlike the SGDBR laser and DBR laser which need a phase-section to tune the FP cavity mode within the reflectivity peaks of the DBRs precisely, the phases of the rectangular ring and the FP cavity in the rectangular ring-FP laser inherently matches when optimally tuned, and the lasing longitudinal mode matches the designed channel spacing defined by the

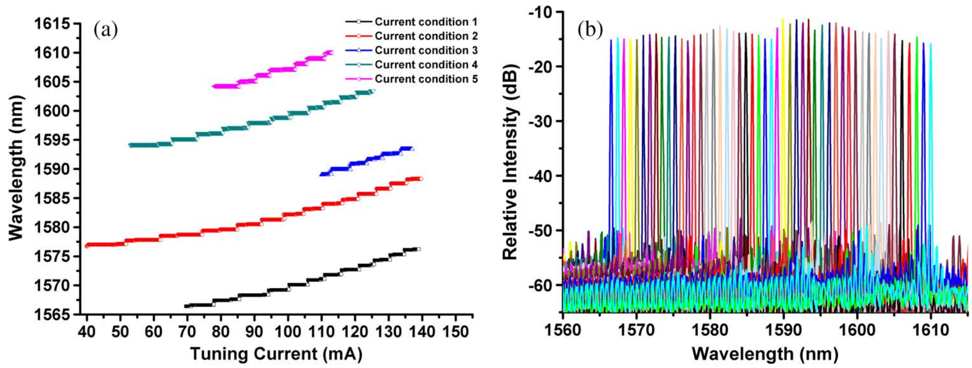


Fig. 4. (a) Measured five single-electrode-tuning curves under different injection currents on the common electrode and the ring electrode and (b) the corresponded superimposed tuning spectra of the 50-channel.

TABLE 1

Injection currents on the three electrodes and the wavelength tuning range for five tuning curves

	I_r (mA)	I_c (mA)	I_t (mA)	Tuning range (nm)
Current Condition 1	61.9	50.3	69 → 138.1	1566.5 → 1576
Current Condition 2	72.8	137.9	40 → 139.5	1576.8 → 1588.2
Current Condition 3	110.4	163	112.1 → 137	1589 → 1593.4
Current Condition 4	136.5	212.6	53 → 126	1594.2 → 1603.4
Current Condition 5	152.8	267.8	81.3 → 117.4	1604.2 → 1610

perimeter of the rectangular ring. Therefore no additional phase tuning section is necessary. However, due to the effective index dispersion of the waveguide, the channel spacing varies slightly, which can result in a wavelength error larger than a tolerance if the tuning range is large. This can be resolved by adjusting the current on the ring electrode (or the common electrode), to slightly shift the selected operating mode of the ring cavity to match the operating frequency grid. Only two electrodes are therefore needed to tune the wavelength accurately, which is simpler than the SG-DBR laser for which three electrodes need to be tuned to set each wavelength channel.

By combining five single-electrode-controlled tuning curves under different current biases on the ring electrode and common electrode, wavelength tuning of fifty channels with 100 GHz spacing covering L band is achieved, with SMSR mostly ranging from 35 dB to 41 dB. Fig. 4(a) shows the static tuning characteristics of the rectangular ring-FP laser, the tuning curve is composed of five segments with injection currents on ring electrode and common electrode fixed at different values, as listed in Table 1. Only the injection current I_t on the tuning electrode is adjusted in each segment. The tuning algorithm and the drive circuit can therefore be very simple due to single-electrode-controlled tuning in each segment. The SMSR can be further increased by lowering the threshold current, which can be achieved by employing high reflective coatings on the deep etched facets of the FP cavity and with improved fabrication process. Fig. 4(b) shows the corresponding superimposed spectra of the 50-channel tuning. The peak intensities in the superimposed spectra are not so flat because of the injection current variation. This can be further optimized by employing a heater for tuning [9], [22].

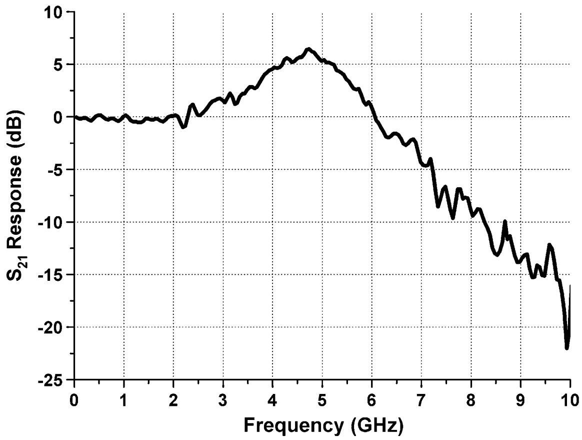
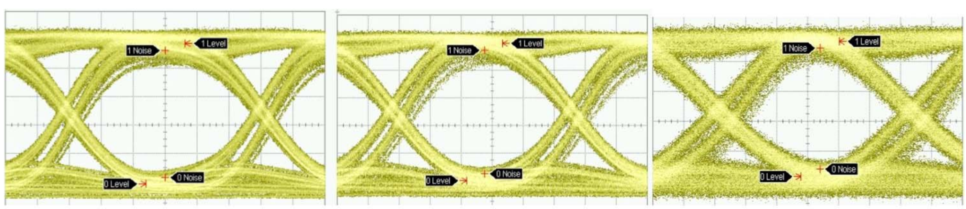


Fig. 5. Small signal frequency response of the laser. The modulation signal is applied on the common electrode.



(a) (b) (c)

Fig. 6. Measured eye diagram at (a) 2.5 Gbps back-to-back. (b) 2.5 Gbps after 20 km SMF transmission. (c) 2.5 Gbps after 50 km SMF transmission.

The TEC is controlled at 20 °C in the above experiments. The large tuning range of fifty channels is mainly based on thermo-optic effect, and the heat is mainly produced by the active waveguides with injection current. Since the temperature coefficient of the gain spectrum shift is about 0.5 nm/K [23], the estimated average junction temperature variation due to the current tuning is about 70 °C, which contributes 35 nm to the extended wavelength tuning range.

For the dynamic characteristics, we first measured the small signal frequency response, as shown in Fig. 5. The bias currents on the three electrodes are $Ir = 61.9$ mA, $Ic = 50.3$ mA, $It = 79$ mA. The relaxation oscillation frequency is 4.7 GHz and the 3 dB bandwidth is about 6.5 GHz. Then 15-bit pseudorandom sequence from a pattern generator is supplied to the common electrode for large signal direct modulation. By designing the ratio between length of the active waveguides under the ring electrode and the perimeter of the rectangular ring to be equal to the ratio between length of the active waveguides under tuning electrode and the length of the FP cavity, mode-hop-free operation is achieved when modulating the rectangular ring-FP laser. Fig. 6 shows the measured eye diagrams at 2.5 Gbps back-to-back with 8.2 dB extinction ratio (a), after 20 km single mode fiber (SMF) transmission with 7.7 dB extinction ratio (b), and after 50 km SMF transmission with 6.7 dB extinction ratio (c). The eye diagrams have multi-traces because the chip is not packaged and the impedance is not perfectly matched, which are to be improved in the future. The optical signal to noise ratio varies from 9.4 dB to 10.6 dB. Fig. 7. shows the measured bit error rate (BER) versus received power for 2.5 Gbps signal after 20 km and 50 km SMF transmission compared with 2.5 Gbps back-to-back signal. The power penalties for 20 km and 50 km SMF transmission are 0.46 dB and 0.93 dB, respectively.

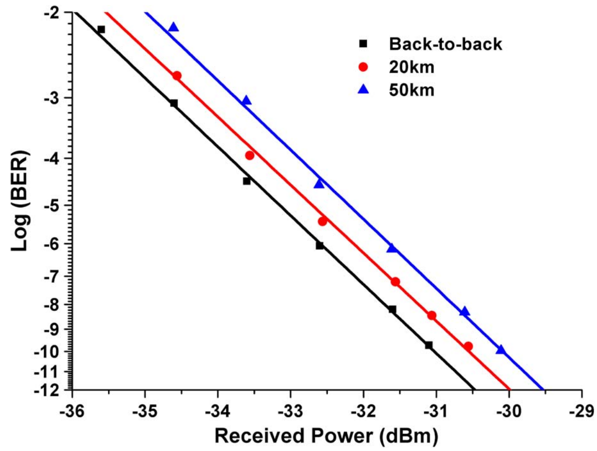


Fig. 7. Measured BER versus received power.

4. Conclusion

We have demonstrated single-electrode-controlled twenty channel 100 GHz spaced wavelength tuning in a half-wave coupled rectangular ring-FP laser, and by combing five single-electrode-controlled tuning curves with different bias currents on fixed electrodes, 50-channels wavelength tuning covering L band with SMSR up to 41 dB is achieved based on thermo-optic effect. Single mode emission with maximum 45.6 dB SMSR is obtained. Direct modulation at 2.5 Gbps is demonstrated with 8.2 dB, 7.7 dB, and 6.7 dB extinction ratio for back-to-back signal, 20 km and 50 km SMF transmission signal, respectively. The power penalties for 20 km and 50 km SMF transmission are 0.46 dB and 0.93 dB, respectively. The laser structure does not involve any gratings or epitaxial regrowth, and has a small size of 0.5×0.5 mm^2. With the advantages of fabrication simplicity, compactness, wide tuning range and simple tuning mechanism, the laser has great potential as a low-cost tunable laser for many applications.

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